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# PARALLAX PROGRAMS AT SUB-MAS ACCURACY LEVEL

C. Ducourant,[1] R. Teixeira,[2] A. Krone-Martins,[1,2] J. F. Le Campion,[1] and G. Chauvin[3]

RESUMEN

Hacemos una presentación de los diversos programas de paralajes desarrollados en el Observatorio de Bordeaux. Mostramos cómo las estrategias de observación, los métodos de reducción y el tratamiento astrométrico global nos permiten alcanzar precisiones mejores que el mili segundo de arco mediante observaciones realizadas con telescopios de 4 metros. Presentamos resultados de un programa en curso para determinar la distancia a la asociación TW Hydrae.

ABSTRACT

We present here the various parallax programs developed at Bordeaux Observatory. We show how the observing strategy, the methods of treatment and the global astrometric treatment allows us to reach sub-milliarcsecond parallaxes with observations performed with 4 meter-class telescopes. We present an ongoing program of distance determination to the TW Hydrae association.

*Key Words:* astrometry

## 1. INTRODUCTION

With the increasing interest for extra-solar planets, parallax measurements appear to be crucial since most of the known stars hosting a planet are situated close to the Sun (d≤100 pc) and therefore accessible to ground-based astrometry.

The use of 4 m-class telescopes allows the determination of parallaxes with sub-milli-arcsecond accuracy after 2 years of regular observations. In such a small time-base program with such a high accuracy aim, it is important to minimize all potential sources of error and bias and to realistically evaluate the errors and their origin.

## 2. SOLAR NEIGHBORHOOD

The Solar neighborhood is an important laboratory to study stars since it allows direct measurements of luminosities, colors, temperatures and masses which are the basis for all analyses in the Galaxy.

Our current knowledge of the solar neighborhood is aptly summarized by the most complete census of stars in the vicinity of sun: the Yale Parallax Catalog (Van Altena et al. 1995, hereafter YPC) which contains 8112 stars with a measured trigonometric parallax. From these, 2300 are not present in the Hipparcos catalog (ESA 1997). From the YPC we will consider the 6289 stars with a measured distance smaller than 100 pc. We give in Figure 1 the histogram of the distances of these nearby stars.

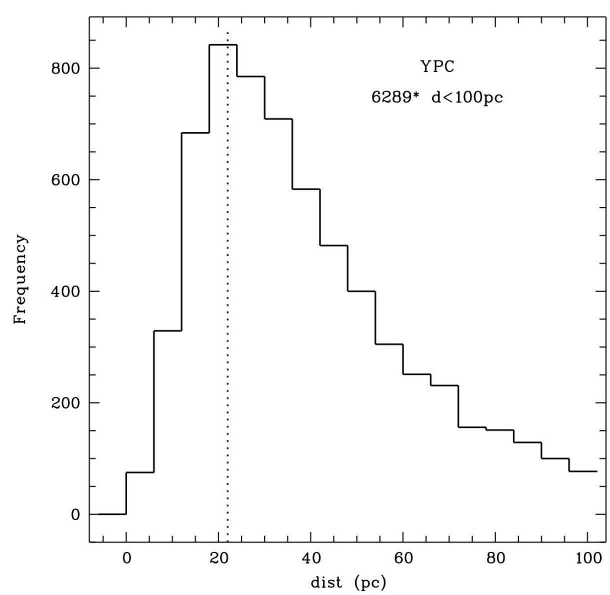


Fig. 1. Histogram of distances of known nearby stars (YPC catalog).

One can notice that most of our knowledge of the solar neighborhood is concentrated in the 20–25 nearest parsecs from the Sun and that after this distance the incompleteness of the sample is clearely shown by the decline of frequencies. We give in Figure 2 the corresponding space density of nearby stars

[1]Observatoire de Bordeaux LAB, France (ducourant, krone, lecampion@obs.u-bordeaux1.fr).

[2]IAG-So Paulo University, Brazil (teixeira@astro.iag.usp.br).

[3]Laboratoire d'Astrophysique de Grenoble, France (Gael.Chauvin@obs.ujf-grenoble.fr).

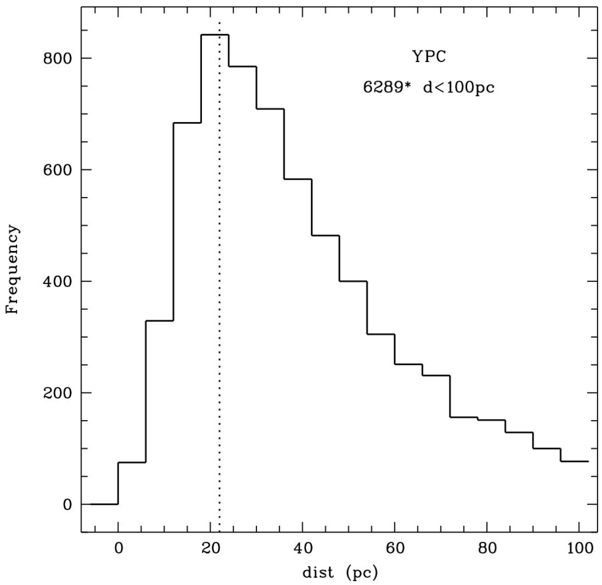


Fig. 2. Space density of nearby stars (YPC, $d \leq 25$ pc) as function of distance from the Sun.

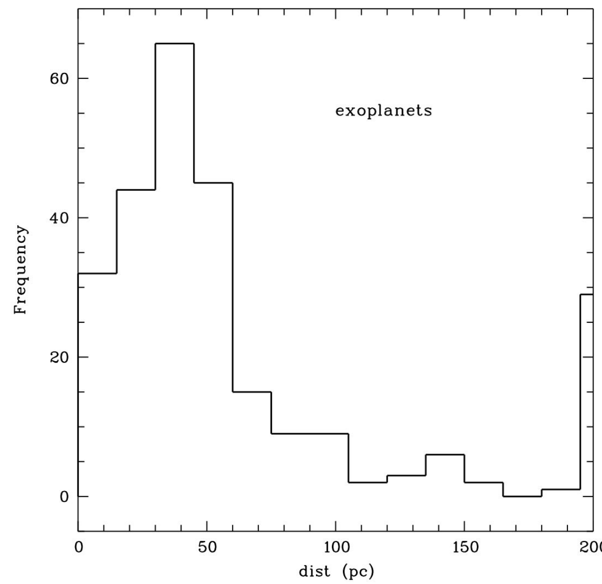


Fig. 3. Distances of stars hosting planets as given in the Encyclopedia of Extrasolar Planets (Schneider 2008).

TABLE 1

REPARTITION OF SPECTRAL TYPES IN THE YPC FOR THE 6289 STARS CLOSER THAN 100 PC

| Sp. Type | Nb of stars |
|---|---|
| O | 32 |
| B | 172 |
| A | 531 |
| F | 867 |
| G | 1473 |
| K | 1875 |
| M | 1023 |

as function of distance from the Sun for these 25 better explored parsecs.

This last figure constitutes evidence of the incompleteness of the YPC even at 10 parsecs from the Sun. We give in Table 1 the content, in terms of spectral types, of the known solar neighborhood as materialized by the YPC.

It is nowadays admitted that M and brown dwarfs should account for about 80% of the local population. It is clear from Table 1 that most of the missing objects of YPC are M dwarfs.

The evidence is given through the analysis of YPC that the solar neighborhood is not well known, even within 25 pc and that most of missing objects are faint M dwarfs. Efforts are being made to complete our solar neighborhood knowledge, especially the RECONS group (Henry, Kirkpatrick, & Simons 1994) which purpose is to discover missing members of the sample of stars within 10 parsecs (32.6 light years), and to characterize all stars within that distance limit.

The solar neighborhood is of fundamental importance in many areas of astronomy, and especially in the quest for extrasolar planets. We present in Figure 3 the histogram of distances of stars hosting planets as given in the Encyclopedia of Extrasolar Planets (Schneider 2008).

Although the vast majority of extrasolar planets have been detected via radial velocities methods (not too sensible to the distance of the stars) we observe that most of the stars hosting planets are located in the solar vicinity (essentially $d \leq 50$ pc). The major reason of that is that programs searching for extrasolar planets target known nearby stars for exhaustive studies of star+planet systems.

## 3. METHODOLOGY

To reach sub-milliarcsecond accuracies, it is important to minimize each potential source of bias and error. The major steps are:

• The use of a 4 m-class (or larger) telescope that allows, through careful observing, to reach measurement errors on a single image lower than 10 mas, as shown in Figure 4 (see also Lazorenko et al. 2007 for

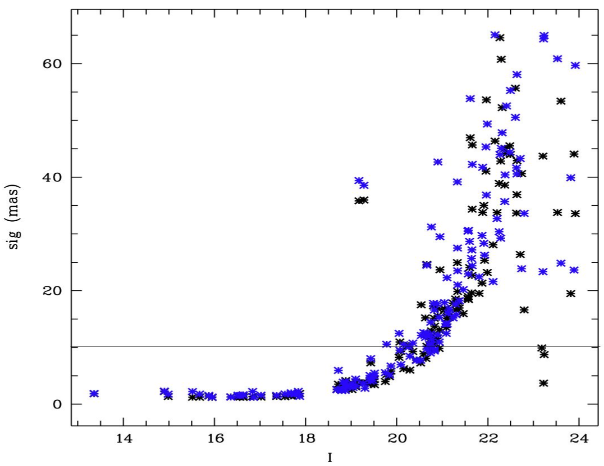


Fig. 4. RMS about mean in $x$, $y$ as function of I magnitude. After doing a linear fit to cross-identify 10 individual frames (NTT/susi2/ ESO-La Silla, pixel=88mas), we computed mean positions and RMS which are a good estimate of the measurement errors. For stars brighter than I=21 errors are lower than 10 mas.

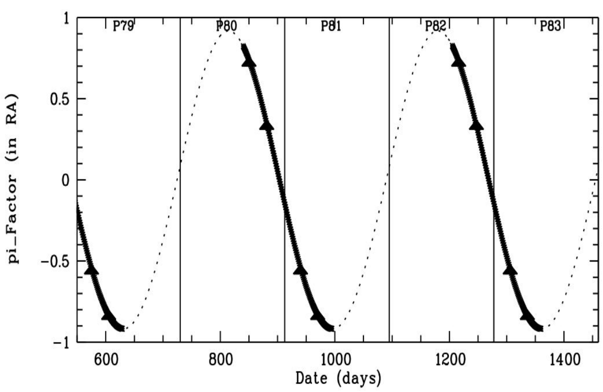


Fig. 5. Parallactic factor in RA (predominant information for the parallax calculation) of targets during observability at HA $\leq$0.5 hour. The dotted line shows the parallactic factor when targets are not observable in astrometric conditions. Filled triangles corresponds to observations.

accurate astrometry at VLT/FORS1 at time scale of few days).

• The observation strategy (time-base, signal-to-noise, frequency, number of repeated frames, distance to zenith, filter, length of program, etc...). It is clear that a high accuracy can be reached with observations spread over a minimum of two years (Ducourant et al. 2007) using a 4 m-class telescope. For this it is important to sample well the parallactic ellipse with regular observations, as shown in Figure 5.

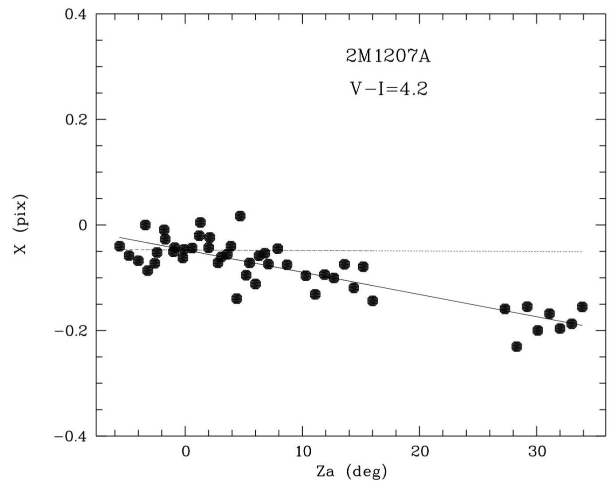


Fig. 6. Atmospheric refraction shift (X) in RA in the I filter as a function of zenith distance for 2M1207. The horizontal line represents the mean atmospheric shift for the reference background stars (Ducourant et al. 2008).

• It appears that a crucial point concerns the zenith distance which has to be minimized in order to minimize differential color refraction effects between target and field stars (see Figure 6 for an example of differential color refraction effect). We remove this effect from the observations by observing the field at various zenith distances and computing the differential shift in RA between field stars and target. Repeated images at each epoch of observation appear to be also important for a correct evaluation of the errors.

• The selection of reference stars used to calibrate pixel scale and orientation of CCD (number, distribution in the field, catalogue astrometry) is an important step. It appears that a catalogue such as 2MASS (Cutri 2003) is suited for this purpose, although it is not a proper motion catalogue and its central epoch is 2000.0. We observe that it introduces less bias in the astrometry than the use of UCAC2 (Zacharias 2004), which is more accurate and constains proper motions, but which is kess dense.

• The global iterative resolution is a crucial point of the treatment. We developed a code of global iterative treatment through a global central overlap procedure (Eichhorn 1997) in order to determine simultaneously the position, the proper motion and the parallax of each well measured object (fit stars) of the field. A typical example of the selection of fit stars is given in Figure 7.

The following equations of condition are written for each star on each of the N frames considered. These

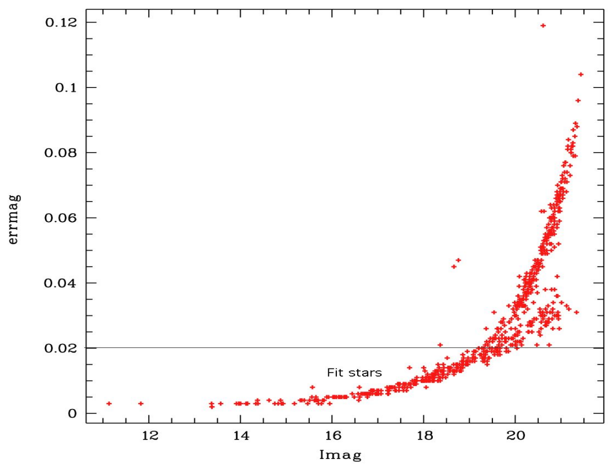


Fig. 7. Selection of fit stars: Main selection is applied on error of measurement (errmag $\leq 0.02$).

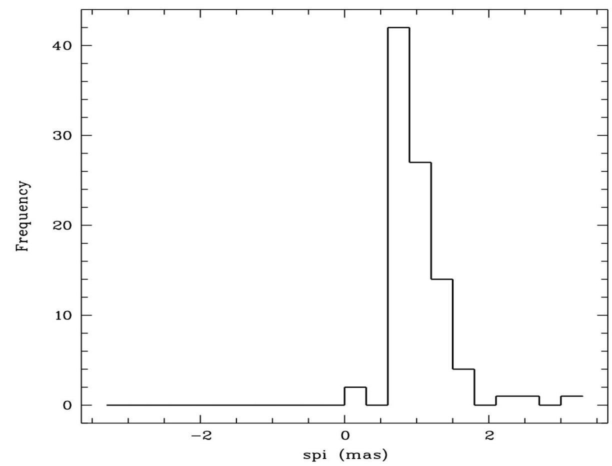


Fig. 8. Resulting precision of the parallax determination of each star in the field of 2M1207.

equations relate the measured coordinates to the stellar parameter:

$$X+\Delta X+\mu_X(t-t_0)+\pi F_X(t) = ax(t)+by(t)+c\,, \quad (1)$$

$$Y+\Delta Y+\mu_Y(t-t_0)+\pi F_Y(t) = dx(t)+ey(t)+f\,, \quad (2)$$

where $(X, Y)$ are the known standard coordinates of the star at epoch $t_0$, $(x(t), y(t))$ its measured coordinates on the frame (at epoch $t$). $\Delta X$, $\Delta Y$, $\mu_X$, $\mu_Y$ and $\pi$ are the unknown stellar parameters and (a,b,c,d,e,f) are the unknown frame parameters which describe the "frame to master frame" transformation. $(F_X, F_Y)$ are the parallax factors in standard coordinates. The unknowns of this large over-determined system of equations are the stellar parameters of each object, and the "plate to master plate" transformation coefficients of each of the $N$ frames considered. The system of equations is singular and therefore the derived solution is not unique; any solution will depend on the starting point of the iterations. The usual technique to obtain a particular solution is to introduce a set of constraints that the solution must satisfy. In this work we chose to set strictly to zero the mean parallax of the reference stars.
A typical example of final precision obtained after such a treatment is given in Figure 8 which presents the histogram of precision of the parallaxes determined for the fit stars in the 2M1207 field.

• The final step consists of converting the relative parallax of the target into an absolute quantity. As a consequence of the least-squares treatment, the parallax (and proper motion) of the target is relative to reference stars (that are supposed to reside at infinite distance). The correction from this relative parallax to the absolute value is performed using a statistical evaluation of the distance of the fit stars using the Besançon Galaxy model (Robin et al. 2003, 2004). The same method is used to convert the relative proper motion of the target to absolute proper motion.

## 4. THE BORDEAUX PARALLAX PROGRAMS

In the last years, our group has developed several programs of parallax measurements with submilliarcsecond accuracies using ESO telescopes aiming at the characterisation of the target through a distance determination. These programs include:

- Systematic search of nearby stars in wide field survey (Ducourant et al. 1998).
- Free-floating brown dwarfs characterisation (Hawkins et al. 1998).
- Halo high velocity white dwarf candidates segregation (Ducourant et al. 2007).
- An accurate distance and mass determination for the first imaged planetary system 2M1207Ab (Ducourant et al. 2008).
- Distance determination of 11 members of the TW Hydrae association (ongoing program).

## 5. DISTANCE DETERMINATION TO THE TW HYDRAE ASSOCIATION

We have started at ESO-NTT a program of observation of the TW Hydrae Association (TWA) in order to measure the distance to 11 of its members. The TW Association (Kastner 1997) appears to be a very young(8 My) and very near (50 pc) association which is a key target of search for very low mass stars, brown dwarfs and planets. From its 25 known members, only 5 have a known parallax (from Hipparcos). The age estimations that appear in the literature are often based on evolutionary models and span a wide range (e.g., 5–12 Myr Song et al. 2003, or 8–20 Myr Boden et al. 2005). However, Ortega et al. (2002) showed that, for a sufficiently young and nearby moving group like $\beta$ Pictoris, a "traceback" age can be derived independent of evolutionary models. It makes this method the most reliable one for measuring ages of young stars. The idea is to trace the Galactic space motions of members of a comoving group backward in time until they occupy a minimum volume in space. Extension of the work of Ortega et al. (2002) would be desirable to reduce the current uncertainties based on evolutionary models.

However, with only four TWA members with Hipparcos parallaxes ($\sigma_{\rm hip} \sim 2-3$ mas) that lie within 100 pc of the Earth, de la Reza et al. (2006) could apply traceback methods to derive a first evaluation of the TWA dynamical age (one Hipparcos star was rejected from their sample). One can easily see from visual inspection of Figure 4 in Song et al. (2003) that with only 4 stars, one gets a very uncertain result. We present in Figure 9 the simulation of a traceback age determination in the case of a cluster similar to TWA with realistic errors on distances and proper motions. We show that the number of objects used in the traceback method is fundamental to seriously constrain the age of the association, principally because this method is very sensitive to the peculiar velocities of objects within the cluster, and also to measurements errors.

With 11 more parallaxes in TWA, it will be possible to derive the association age using a total of 16 stars with known parallax (4 Hipparcos; 2M1207, Ducourant et al. 2008; and 11 from this proposal). This will ensure a very good estimation of the dynamical age of TWA.

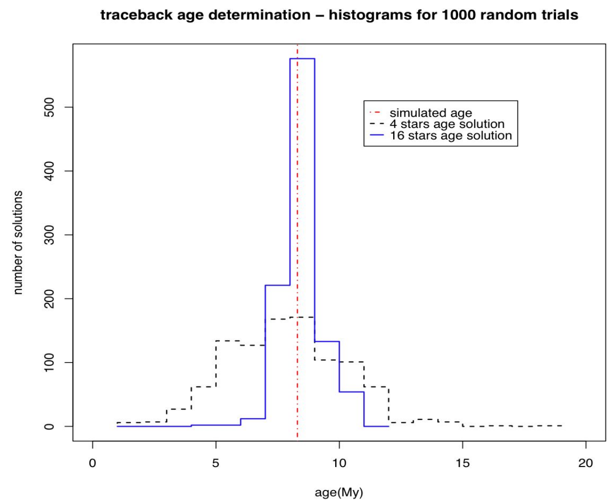


Fig. 9. Traceback age of a simulated TWA. We present the result of a simulation of TWA cluster: 25 stars placed at 60 pc from the Sun in a 14.5 pc radius sphere, with common proper motion+ random peculiar velocities (2 km s$^{-1}$) evolved during 8.3 Myr. Then an observation of the 25 members is simulated $(\alpha, \delta, \mu, \pi)$ and Gaussian random errors such as those expected from this work ($\sigma_\pi = 1$ mas, $\sigma_\mu = 1$mas yr$^{-1}$) are added to those observations. Finally a trace-back method is applied to randomly selected subsamples (1000 trials) of 4 and of 16 stars of the cluster to determine the age corresponding to the minimum volume occupied. In this diagram we present the histogram of the ages so determined for 4 and for 16 objects. The vertical line indicates the "true" age of the cluster. This result demonstrates the necessity to use a larger sample of stars with known accurate parallax than de la Reza et al. (2006) (4 stars only), to properly constrain the age determination of TWA as proposed in the present proposal because the traceback method is seriously sensitive to the peculiar velocities of objects within the cluster and to parallax errors, showing that with only 4 stars the age determination is not reliable enough.

## 6. CONCLUSION

Our various works in the field of astrometry and especially of measuring trigonometric parallaxes show that every step is important and that it is possible to derive parallaxes with sub-milliarcsecond precisions for observations performed with a time basis of 2 years. We confirm that the global treatment of the data is important and leads to more precise results. In 2012 Gaia will start observing the Galaxy in such a way as to render obsolete most of the ground-based astrometric work. Nevertheless the publication of the Gaia catalogue will not appear before 2019, and until then a lot of interesting and exciting topics can be investigated through trigonometric parallax determinations.

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